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Search for resonances in the ^{22}Na$(p,\gamma)^{23}$Mg reaction

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The reaction ^{22}Na$(p,\gamma)^{23}$Mg has been investigated in the energy range $E_p = 0.4-1.27$ MeV using a radioactive ^{22}Na target. Upper limits for the γ yield have been determined for transitions to states in ^{23}Mg up to $E_x = 4.4$ MeV. The upper limits for the expected resonances in this energy range are more than an order of magnitude weaker than previously predicted. These upper limits are compared with shell model calculations.

I. INTRODUCTION

The understanding of the *rp*-process nucleosynthesis[1] in the Ne-Na-Mg region is of particular interest for the interpretation of ^{22}Ne anomalies in meteoritic inclusions[2] as the decay product of ^{22}Na ($t_{1/2} = 2.6$ yr). Several reaction sequences, depending on the temperature and density conditions, may lead to the formation of ^{22}Na. Most favorable is the Ne-Na cycle[3]

$$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}(\beta^+\nu)^{21}\mathrm{Ne}(p,\gamma)^{22}\mathrm{Na}\ ,$$

where ^{22}Na is formed by well-understood proton capture reactions.[4,5] The abundance of ^{22}Na, however, also depends critically on the rates of possible depletion reactions, the most important being ^{22}Na$(p,\gamma)^{23}$Mg. Another mechanism for producing ^{22}Na, more likely to occur in high-temperature and high-density conditions,[1,6] is

$$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}(\beta^+\nu)^{22}\mathrm{Na}\ .$$

In this case the production rate also depends on the rate of the competing proton capture rate on ^{22}Mg.

While the reaction rate for ^{22}Mg$(p,\gamma)^{23}$Al has recently[7] been deduced from a measurement of its resonance energy coupled to a shell-model calculation of its resonance strength, only theoretical estimates for the ^{22}Na$(p,\gamma)^{23}$Mg reaction rate exist. Little was known about the structure of the compound nucleus ^{23}Mg above the proton threshold at $Q = 7.58$ MeV when the first estimate was published.[1] Following this, the ^{25}Mg$(p,t)^{23}$Mg (Ref. 9) and ^{24}Mg$(^3$He$,\alpha)^{23}$Mg (Ref. 10) reactions were used to identify proton unbound levels in ^{23}Mg (Fig. 1). However, these experiments did provide neither unique spin and parity assignments for the levels nor information about the partial widths necessary to calculate the resonance strengths for the ^{22}Na(p,γ) reaction. Therefore the direct measurement is highly desirable.

Because of the relatively long half-life of ^{22}Na ($t_{1/2} = 2.6$ yr), the use of a radioactive target is more favorable than the use of a radioactive beam.[11] The radioactive ^{22}Na target, however, produces an extremely large flux of 511 and 1275 keV γ rays. To circumvent this problem, Rolfs and Kavanagh[12] have developed a new type of detector, which is not sensitive to γ radiation below $E_\gamma = 2.2$ MeV. A disadvantage of this detector is the lack of energy resolution, which requires ultraclean ^{22}Na targets. We therefore chose a more traditional experimental approach for the direct measurement of the ^{22}Na$(p,\gamma)^{23}$Mg reaction above a proton energy of $E_p = 0.400$ MeV.

II. EXPERIMENTAL EQUIPMENT AND SETUP

Proton beams of 10–30 μA were provided by the 3 MV Tandem Pelletron at the Kellogg Radiation Laboratory over the energy range of 0.400–1.275 MeV. The proton beam passed through a Ta collimator and was directed onto the target. The targets were mounted normal to the beam and directly watercooled. A liquid-nitrogen-cooled Cu tube was extended to within 10 cm of the target to reduce carbon deposition. During the experiment a slowly varying (0.1 Hz) ramping voltage (0 to +8 kV) was applied to the electrically insulated target chamber. This allowed us to measure the excitation function over an energy range of 8 keV per beam-energy step. The accumulated charge was measured continuously as a function of the ramping voltage and could be corrected for leakage current. This leakage current, due to the water cooling, was $\leq 1\ \mu$A.

The production and properties of the ^{22}Na target have been described in detail elsewhere,[13] and will be discussed here only briefly. The ^{22}Na targets were prepared from an aqueous ^{22}NaCl solution (Amersham Corporation) with a specific activity of 1.3 mCi/ml. Three to five drops of the solution were applied to the backing and slowly dried under a heat lamp. This procedure was repeated until the desired activity was reached. The backing consisted of 0.5 mm Ta with a 0.05 mm deep reces-

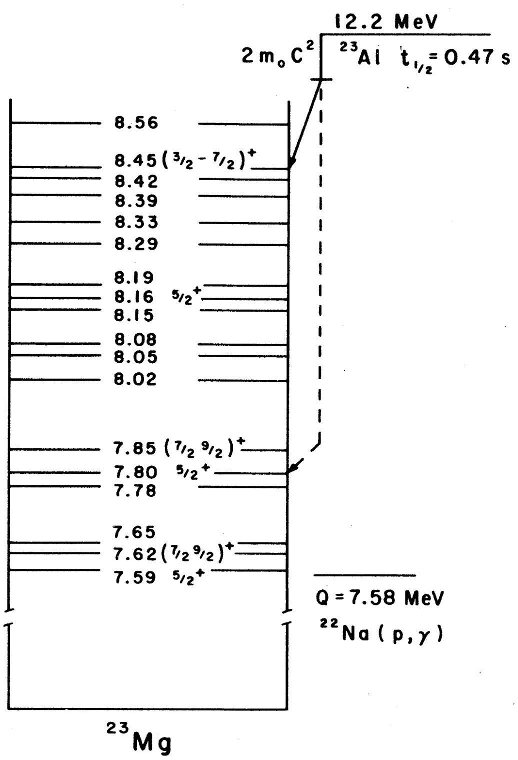

FIG. 1. Level structure of ^{23}Mg above the proton threshold (Refs. 9, 10, and 14).

sion (diameter 6 mm) to physically constrain the activity. The Ta previously was coated with a 50 μg/cm^2 Ni layer to minimize the diffusion of the Na into the backing (see Ref. 13). The total activity of the target was limited by the counting rate in the γ detector to 60 μCi. This activity, distributed over an area of 0.28 cm^2, corresponds to a ^{22}Na areal density of 8.9×10^{14} atoms/cm^2 (see Table I and Ref. 13).

Independent tests indicated that the loss of the target material due to proton bombardment could be kept to $\leq 10\%$ over a period of 1 week by defocusing the beam of 20 μA to produce a uniform beam spot (4–5 mm diameter). Activity scans of the targets before and after runs show no significant change in the ^{22}Na distribution (see Ref. 13).

Contaminants in the ^{22}NaCl solution were measured using known, strong (p,γ) resonances and are listed in Table I; for details see Ref. 13. The large amount of Si in the solution arises from radiation damage to the glass container in which the aqueous solution was contained. Heavier elements, $Z \geq 18$, could not be measured directly with this method, because there are no strong resonances in the energy region investigated. Ca, Cu, and Fe were indicated by the supplier, but they produce no significant beam-induced γ background and contribute only to the total target thickness.

TABLE I. Measured composition of the ^{22}Na target (Ref. 13).

Element	n (atoms/cm^2)
^{22}Na	$(8.9\pm0.4)\times10^{14}$
^{23}Na	$(1.1\pm0.2)\times10^{15}$
Cl	$(1.2\pm0.6)\times10^{15}$
Mg	$(3.2\pm0.8)\times10^{15}$
Si	$(1.1\pm0.1)\times10^{17}$
$Z>18$	$(\simeq 10^{17})$

Because ^{22}Na and ^{23}Na have the same chemical properties, the ^{23}Na contaminant was used to measure the depth profile and the total thickness of the ^{22}Na target using the narrow ($\Gamma < 0.07$ keV) $E_R = 0.677$ MeV resonance in ^{23}Na$(p,\gamma)^{24}$Mg.[14] Prior tests showed that the amount of ^{23}Na on the backing itself is negligible.[13] The yield curve over the resonance is shown in Fig. 2. The observed resonance energy of 0.677 MeV agrees well with the known value, proving that the Na is on the surface of the target, as expected from previous tests.[13] The observed target thickness is $\simeq 3$ keV at $E_p = 0.677$ MeV with 1 keV of the thickness arising from the energy loss of the protons in the Si, and the remaining target thickness attributed to the heavier elements mentioned above. This measurement was repeated several times during the course of the experiment to monitor the target stability.

The γ radiation was observed with a 35% Ge detector at 0° with respect to the beam. The high γ-ray flux from the decay of ^{22}Na made it necessary to shield the detector from the target in order to keep the counting rate below 25 kHz ($\simeq 40\%$ computer dead time). To achieve this with the highest possible detection efficiency for the expected high-energy γ rays ($E_\gamma \simeq 8$ MeV) several tests were made. Mounting an Al target in the same geometry, the γ-ray yield of the known 0.992 MeV resonance in ^{27}Al$(p,\gamma)^{28}$Si (Ref. 14) for the transition $R \rightarrow 1.78$ MeV was measured relative to the yield of the $E_\gamma = 1.78$ MeV transition from the decay of the first excited state of ^{28}Si to its ground state. The optimal configuration is one which preferentially absorbs the low-energy γ rays while maintaining high efficiency for the high-energy γ rays. These measurements were made for several combinations of Pb thickness and target-

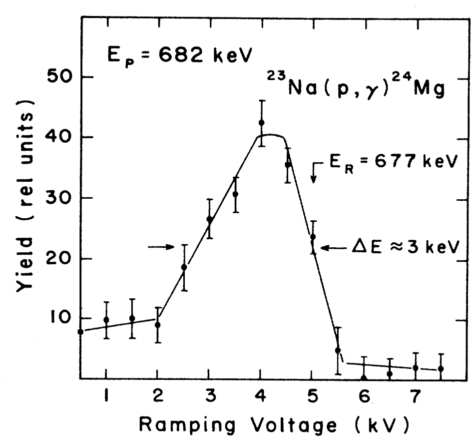

FIG. 2. Yield curve of the ^{23}Na$(p,\gamma)^{24}$Mg resonance at $E_R = 677$ keV; for details see text.

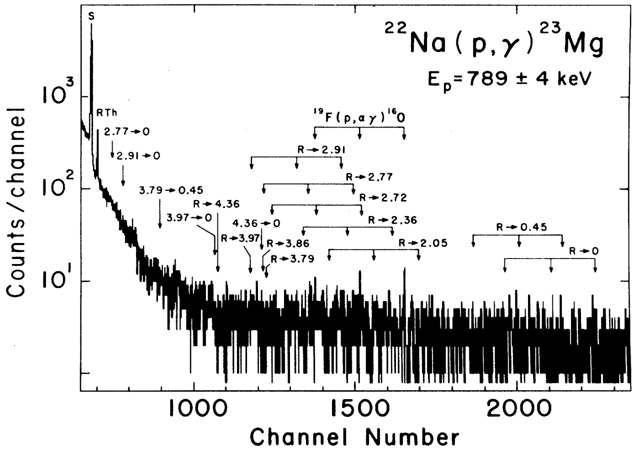

FIG. 3. Typical γ spectrum obtained at $E_p = 789 \pm 4$ keV. Indicated are the positions of analyzed γ transitions expected in ^{23}Mg; summing peaks are identified by the letter *S*.

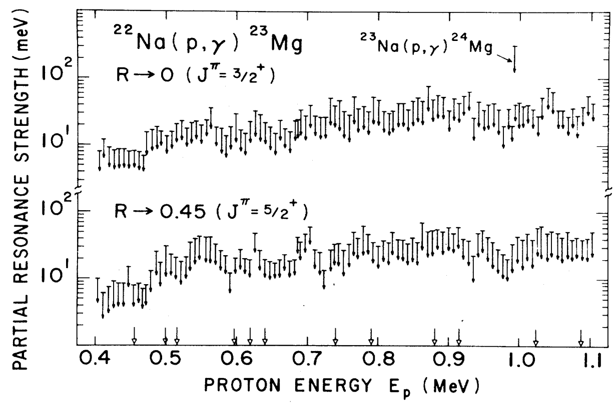

FIG. 4. Excitation function of the transition to the ground state (top) and the first excited state (bottom) of ^{23}Mg. Only every third point is plotted in the smooth regions of the excitation function. The open arrows at the bottom of the graph indicate the position of expected resonances.

detector distance. The best results were obtained with 22 mm of Pb between the target and the detector and a total detector distance of 35 mm.

A commercially available amplifier (ORTEC 572) was used to reject pileup events. The measured energy resolution of the detector at high rates ($\simeq$25 kHz) was 3.5 keV at $E_\gamma = 1.33$ MeV. To determine the γ efficiency, the ^{22}Na target was placed close to an Al target (100 μg/cm^2) mounted in the target chamber to reproduce the high counting rate. The thick target γ-ray yield of the strong ^{27}Al$(p,\gamma)^{28}$Si resonance at 0.992 MeV was measured and from the known resonance strength[15] and branching ratios of the γ-ray decay,[16] the absolute detector efficiency was determined for γ energies between 2.4 and 11 MeV. At lower energies no reaction lines could be observed due to the high ^{22}Na activity.

The γ-ray pulse height was stored along with the ramping voltage in a 4096$\times$16 data array for off-line analysis. The dead time was determined by standard pulser techniques.

III. DATA ANALYSIS AND RESULTS

A comparison with the γ branching ratios of states in the mirror nucleus ^{23}Na, in the same excitation energy range, suggests a decay mainly to the ground and first excited ($E_x = 0.45$ MeV) states of ^{23}Mg. The $E_\gamma = 0.45$ MeV transition cannot be observed due to the intense γ background from the decay of ^{22}Na. Thus the two primary transitions were monitored in an on-line analysis during the course of the experiment. In a subsequent off-line analysis all possible transitions above the pileup peak of the 1.275 MeV γ ray were analyzed. A typical γ spectrum is shown in Fig. 3.

For the analysis of the data the 4096$\times$16 data arrays were broken up into three arrays and the events were

TABLE II. Experimental upper limits of the partial resonance strengths (in meV) for the indicated transitions at the energies where states have been observed (Refs. 9 and 10).

E_p (lab) (MeV)	$R \rightarrow E_x$ (MeV) 0.0	0.45	2.05	2.36	2.72	2.77	3.79	3.86	3.97	4.36
0.456	9	9	11	13	19	17	11	9	12	8
0.499	14	25	35	32	28	22	19	16	15	21
0.515	23	21	17	19	23	22	11	14	13	13
0.597	30	20	78	25	25	23	14	14	19	15
0.619	17	21	650[a]	50	30	43	21	18	17	32
0.640	18	18	53	35	35	42	14	18	13	14
0.740	30	44	46	42	48	55	50	50	48	29
0.791	39	44	23	32	30	30	30	30	29	26
0.853	55	35	56	39	59	59	36	79	34	43
0.881	72	68	330[a]	220[a]	300[a]	117	100	168	150	100
0.915	56	43	145	430[a]	100	100	62	60	64	65
1.024	27	70	60	60	100	63	57	48	50	45
1.087	40	39	150	99	280[a]	105	130	100	190	96
1.234	44	43	109	300[a]	220[a]	130	130	114	155	97
1.271	41	28	110	400[a]	400[a]	89	100	260[a]	256[a]	110

[a]Overlap with background line.

TABLE III. Observed and predicted strengths for resonances in ^{22}Na$(p,\gamma)^{23}$Mg; for details see text.

E_x[a] (MeV)	J^{π}[b]	E_p (lab) (MeV)	Resonance strength (eV) Expt.	Ref. 8[c]
8.014	$\frac{3}{2}^-$	0.456	$\leq 1.8\times10^{-2}$	2.4×10^{-1}
8.055	$\frac{5}{2}^-$	0.499	$\leq 3.9\times10^{-2}$	3.8×10^{-1}
8.071	$\frac{5}{2}^+$	0.515	$\leq 4.4\times10^{-2}$	1.5
8.149	$\frac{3}{2}^+$	0.597	$\leq 5.0\times10^{-2}$	4.3×10^{-1}
8.170	$\frac{5}{2}^+$	0.619	$\leq 3.8\times10^{-2}$	1.5
8.190	$\frac{7}{2}^-$	0.640	$\leq 3.6\times10^{-2}$	4.6×10^{-1}
8.285		0.740	$\leq 7.4\times10^{-2}$	
8.334		0.791	$\leq 8.3\times10^{-2}$	
8.393		0.853	$\leq 9.0\times10^{-2}$	
8.420		0.881	$\leq 1.4\times10^{-1}$	
8.453		0.915	$\leq 9.9\times10^{-2}$	
8.557		1.024	$\leq 9.7\times10^{-2}$	
8.617		1.087	$\leq 7.9\times10^{-2}$	
8.758		1.234	$\leq 8.7\times10^{-2}$	
8.793		1.271	$\leq 6.9\times10^{-2}$	

[a]Reference 10 for $E_x \leq 8.2$ MeV; Ref. 9 for $E_x \geq 8.2$ MeV.
[b]Tentative spin assignment adopted from Ref. 8.
[c]Corrected for new values of E_x (Ref. 9).

projected on to the E_γ axis. The resulting three spectra represent the γ spectra for three consecutive ramping ranges of $\frac{1}{3}$ of the total ramping energy of 8 keV. The energies of possible primary transitions were calculated using the median energy for each energy step and a Q value of 7.578 MeV.[18] The Doppler shift and γ recoil were included in these calculations. Regions of ±2 channels ($\simeq\pm7$ keV) around the expected positions were analyzed. This width includes the errors in the Q value (1.9 keV), energy calibration (2 keV), and incident proton energy (1 keV), which result in a total uncertainty of $\simeq1$ channel. The width of high-energy γ-ray lines is estimated to 3 channels from the observed width of strong γ lines of $E_\gamma \simeq 8$ MeV, which were observed in the reactions ^{23}Na$(p,\gamma)^{24}$Mg and ^{30}Si$(p,\gamma)^{31}$P.

Since at the excitation energies of ^{23}Mg under investigation here, $E_x = 7.97-8.63$ MeV, no particle channels except protons are open, it can be assumed that the width Γ of possible resonances in ^{22}Na$(p,\gamma)^{23}$Mg is smaller than the observed target thickness of ≈3 keV. This assumption is supported by the width of the corresponding states in the analog nucleus ^{23}Na.[14] The γ yields can then be converted into partial resonance strengths $\omega\gamma_i$ using the well-known relation for the thick target yield of a narrow resonance:[19]

$$\omega\gamma_i = \frac{2\epsilon}{\lambda^2}\frac{m_t}{m_p+m_t}\frac{I_\gamma}{(1-\mathrm{DT})\eta_\gamma N_p},$$

with ϵ the stopping power, λ the center-of-mass proton wave length, $m_t(m_p)$ the mass of the target (projectile), I_γ the intensity of the γ line, DT the dead time of the computer ($\simeq40\%$), η_γ the γ efficiency and N_p the total number of incident particles. The stopping power ϵ was calculated from the ratio of the target thickness ΔE_t and the number of target atoms per cm^2. The target thickness as a function of the proton energy was determined from the excitation functions of the strong ^{29,30}Si$(p,\gamma)^{30,31}$P resonances at $E_R = 0.416$, 0.620, and 0.983 MeV,[14] and of the ^{23}Na$(p,\gamma)^{24}$Mg resonance at $E_R = 0.677$ MeV (Sec. II). The results have not been corrected for possible angular distribution effects. Systematics of angular distributions of reactions with similar Q values[14] suggest a maximum correction of 50%.

No resonance was observed in any of the analyzed transitions for proton energies of $E_p = 0.400-1.100$ MeV. In addition, no resonances were observed for the states at $E_x = 8.758$ and 8.793 MeV.[10] The upper limits of the resonance strength for the ground-state transition and the transition to the first excited state are shown in Fig. 4. The resulting upper limits (1 standard deviation) for the partial resonance strengths for the transitions to the ground and first ten excited states in ^{23}Mg are listed in Table II, for proton energies that correspond to known states in ^{23}Mg.[9,10]

IV. DISCUSSION

To assign upper limits for the total resonance strengths of the expected resonances, assumptions about the dominant γ decay of these states have to be made. As already pointed out by Wiescher and Langanke,[8] a comparison with the mirror nucleus ^{23}Na suggests γ decay mainly to the ground and first excited state. Adopting this assumption yields the upper limits for the total resonance strengths listed in Table III. For comparison, the estimates by Wiescher and Langanke[8] are also given. Their values are corrected for slight changes in the excitation energy[10] by scaling the proton widths with the relative change of the Coulomb penetrabilities. The resulting

TABLE IV. Comparison of shell-model calculations and experiment (Ref. 14) for the transition to the ground state and to the first excited state in the analog nucleus ^{23}Na.

E_i (MeV)	J^{π}	Γ_γ (eV) (calc.) g.s.	0.44	Γ_γ (eV) (expt.; Ref. 14) g.s.	0.44
2.08	$\frac{7}{2}^+$	2.7×10^{-3}	1.5×10^{-2}	$(1.5\pm0.2)\times10^{-3}$	$(1.5\pm0.2)\times10^{-2}$
2.39	$\frac{1}{2}^+$	4.2×10^{-4}	2.1×10^{-4}	$(5.3\pm1.0)\times10^{-4}$	$(2.9\pm0.5)\times10^{-4}$
2.98	$\frac{3}{2}^+$	6.5×10^{-2}	4.0×10^{-2}	$(7.6\pm1.5)\times10^{-2}$	$(5.5\pm1.1)\times10^{-2}$
3.91	$\frac{5}{2}^+$	2.6×10^{-2}	1.1×10^{-3}	$(4.9\pm0.9)\times10^{-2}$	$(4.8\pm1.1)\times10^{-3}$

TABLE V. Shell-model predictions of the γ transition width $(2J+1)\Gamma_\gamma$ for the transition to the ground state and to the first excited state in ^{23}Mg in the excitation range of $E_x=8-9$ MeV.

J^π	$(2J+1)\Gamma_\gamma$ (eV) $E_i \to$ g.s.	$E_i \to 0.45$
$\frac{1}{2}^+$	0.7 −0.8	$3\times10^{-4}-7\times10^{-3}$
$\frac{3}{2}^+$	0.4 −0.8	$5\times10^{-2}-2$
$\frac{5}{2}^+$	2 −4	$2\times10^{-3}-4$
$\frac{7}{2}^+$	0.06−0.3	$2\times10^{-1}-4$
$\frac{9}{2}^+$		$1\times10^{-5}-3\times10^{-1}$

upper limits (Table III) are in all cases but one ($E_R=0.881$ MeV) below 100 meV and consequently at least a factor of 10 smaller than the estimates[8] in the overlapping energy range. This result is somewhat surprising since many (p,γ) reactions with similar Q values in this mass region exhibit at least one resonance[14,17] with a strength of 0.5−1.0 eV in the same proton energy range as covered in this experiment, e.g., ^{22}Ne$(p,\gamma)^{23}$Na, ^{23}Na$(p,\gamma)^{24}$Mg. One exception[20] is the reaction ^{26}Al$(p,\gamma)^{27}$Si, where the resonance strengths for all observed resonances are smaller than 100 meV.

At proton energies above 0.4 MeV, the proton width is, in general, larger than the corresponding γ width. Therefore the present results indicate much smaller γ widths than previously assumed.[8] Since no experimental information exists, Wiescher and Langanke[8] assumed γ widths deduced from the average of the observed transition-strength distributions[21] ($E1=3\times10^{-3}$ W.u., $M1=0.3$ W.u., $E2=3$ W.u.). However, these distributions cover a range of 5 orders of magnitude and it is therefore entirely possible that the choice of the averages of these distributions could overestimate the actual γ widths by as much as 2 orders of magnitude. Furthermore, most of the known values for Γ_γ are for transitions between states below an excitation energy of 4 MeV. At these excitation energies the nuclear states have a predominantly single-particle structure, while at the higher excitation energies of interest here, $E_x=8-9$ MeV, the states are more likely of 2p-2h nature, indicating smaller γ transition strengths.

To obtain a more realistic estimate for the γ widths, shell-model calculations for an $A=23$ nucleus were performed. Using the code OXBASH (Ref. 22) and Wildenthal's universal sd interaction[23] for the mass range $A=17-39$, the energies of the positive-parity states ($J^\pi \le \frac{9}{2}^+$) were calculated up to an excitation energy of 12 MeV. Subsequently, the reduced γ transition probabilities for $M1$ and $E2$ transitions for all of these states to the ground and the first excited state were calculated. For the analog nucleus ^{23}Na, the shell-model results are in reasonably good agreement with experimental values (Table IV), which were derived for states with known half-lifes and γ branching ratios.[14] To compare the theoretical values with the present experimental upper limits, $(2J+1)\Gamma_\gamma$ was calculated for the transitions to the ground and first excited states. The shell-model results range from 0.06 eV to 4 eV for the ground-state transition and from 1×10^{-5} eV to 4 eV for the transition to the first excited state (Table V). The experimental upper limits for the corresponding transitions are $\le 0.13- \le 1.0$ eV and $\le 0.13- \le 1.0$ eV, respectively. Both experimental and theoretical values are, on the average, an order of magnitude lower than previously predicted.[8]

To obtain reliable experimental stellar reaction rates further experiments with an improved sensitivity are necessary. This can be achieved either by the use of improved targets, e.g., isotope-separated, implanted targets, or by the use of the recently developed heavy water (D_2O) detector.[12]

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